Final report for AOARD project # 114049:
"Fabrication of metamaterial devices by drawing techniques"

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Title: Fabrication of metamaterial devices by drawing techniques

Metamaterials – artificially structured materials with properties emerging from their structure rather than constituents – enable unprecedented control over propagation of light with applications such as lenses beating the diffraction limit for hyperfine imaging and lithography. Fabrication of metamaterials for the optical regime is extremely difficult, as highly structured, repetitive metallic features at the nanoscale are required. The main barrier to experimental realization of optical metamaterials is the great difficulty of fabricating on this scale. Approaches divide into two main classes. Bottom-up approaches include molecular self-assembly and self-ordering. Whilst having the advantage of self-assembly, the structures are, as a result, typically quite limited as it is difficult to introduce spatial variations required for most devices. Top-down approaches such as e-beam or focused ion beam lithography can readily produce complex structures, however they have to individually create every part of the structure, which is a time consuming use of extremely expensive equipment, and limited to shallow, mostly 2D, structures. No existing technology is suitable to produce materials structured at nanoscopic scales in bulk.

In a previous AOARD funded project, we had made considerable advances towards a novel and practical nanofabrication technique for metamaterials for frequencies from the terahertz (THz) through mid-infrared to visible light.

With this technique, for the first time, inexpensive volume production of metamaterials will be possible. Our technique relies on reducing scales by viscous drawing, the technology used for making optical fiber. In our previous project we have demonstrated the fabrication of drawn metamaterials with designed electric and magnetic properties at THz frequencies, including negative permeability and permittivity. We also demonstrated that the technique can potentially be used for shorter wavelengths, including in the visible.

The aim of this project was to work towards the demonstration of metamaterial fibres devices, on the example of sub-wavelength THz waveguides. Such waveguides guide light in a core having a cross-section much smaller than the wavelength. Such confinement is impossible in pure metallic or dielectric waveguides. It has been shown theoretically that such confinement can be achieved in waveguides using metamaterials. Waveguides smaller than the wavelength are of great importance

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14. ABSTRACT
Metamaterials ? artificially structured materials with properties emerging from their structure rather than constituents ? enable unprecedented control over propagation of light with applications such as lenses beating the diffraction limit for hyperfine imaging and lithography. Fabrication of metamaterials for the optical regime is extremely difficult, as highly structured, repetitive metallic features at the nanoscale are required. The main barrier to experimental realization of optical metamaterials is the great difficulty of fabricating on this scale. Approaches divide into two main classes. Bottom-up approaches include molecular self-assembly and self-ordering. Whilst having the advantage of self-assembly, the structures are, as a result, typically quite limited as it is difficult to introduce spatial variations required for most devices. Top-down approaches such as e-beam or focused ion beam lithography can readily produce complex structures, however they have to individually create every part of the structure, which is a time consuming use of extremely expensive equipment, and limited to shallow, mostly 2D, structures. No existing technology is suitable to produce materials structured at nanoscopic scales in bulk.

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for miniaturization of integrated devices in terahertz and mid-IR (e.g. at THz the waveguide diameter will reduce from a few millimeters to a few hundreds of microns, making the waveguide flexible).

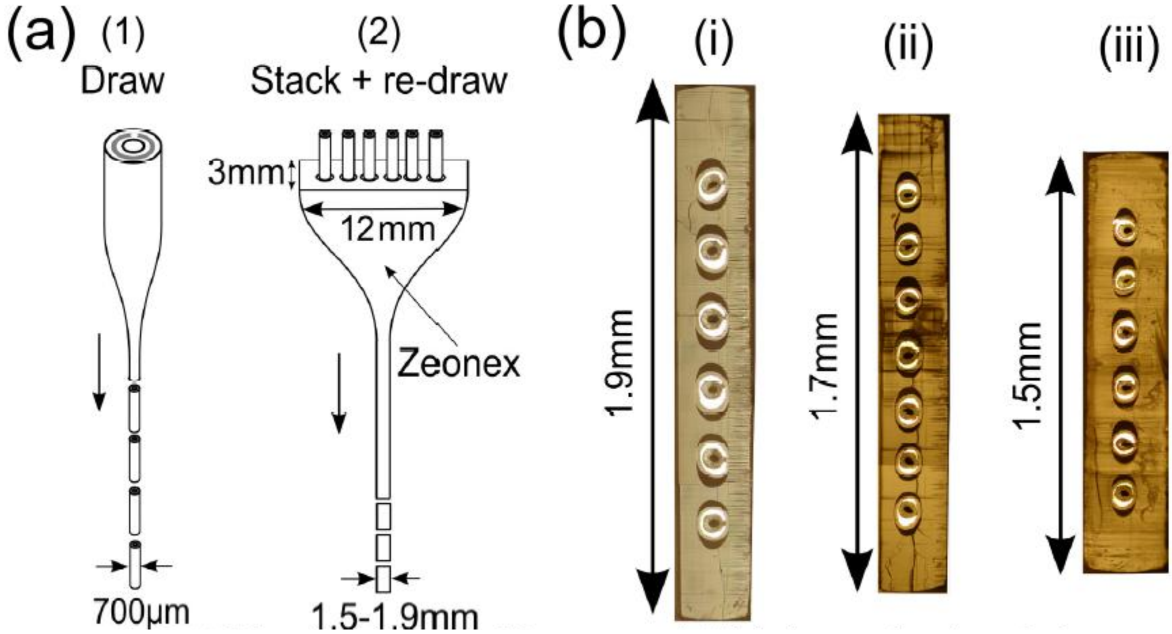

Figure 1: from Ref. 1: Schematic of the stack-and-draw metamaterial fabrication procedure. A cm-sized preform similar to that presented in Fig. 1(a) is drawn down to a 700 µm fiber and cut into 30 cm pieces. Each piece is inserted into the six holes of a 12 × 3 mm2 rectangular Zeonex preform. This entire structure is re-drawn down to rectangular fibers of 1.5-1.9 mm. (b) Optical microscope image of the cross section of (i) 1.9 mm, (ii) 1.7 mm and (iii) 1.5 mm wide rectangular fiber, containing six slotted resonators. Note that fibers (i) and (ii) have been polished on the sides.

Results Summary: The fabrication of metamaterial based waveguides requires the integration of a number of resonators into the same fibre. We have successfully demonstrated the integration of 6 simultaneously drawn split ring resonators, as shown on Figure 1, and experimentally determined their resonant magnetic response in the THz. With these slabs of drawn metamaterials, we have produced the first truly three dimensional bulk metamaterial samples for THz, and were able to measure the bulk response of several metamaterial layers. The findings were published in Optics Express [1] and presented at several conferences [2,4-5].

We have completed a theoretical and numerical investigation of sub-wavelength guidance in metamaterial fibres, by deriving and solving the full analytic modal equations for hollow core waveguides surrounded by strongly anisotropic metamaterials with realistic material properties. This was necessary as drawn metamaterials have extreme anistrotropy unlike any found in nature, and the study of waveguides using such materials had never been done before. We have successfully extracted conditions for light to be guided in such fibres, and numerically demonstrated that cores one tenth of the wavelength in size can confine radiation with over 90% of the power still in the core – a feat impossible with conventional metals or dielectrics. Two manuscripts on the full theoretical and numerical analysis are about to be submitted [10,11], and results were presented at the META 2012 conference in Paris [3].

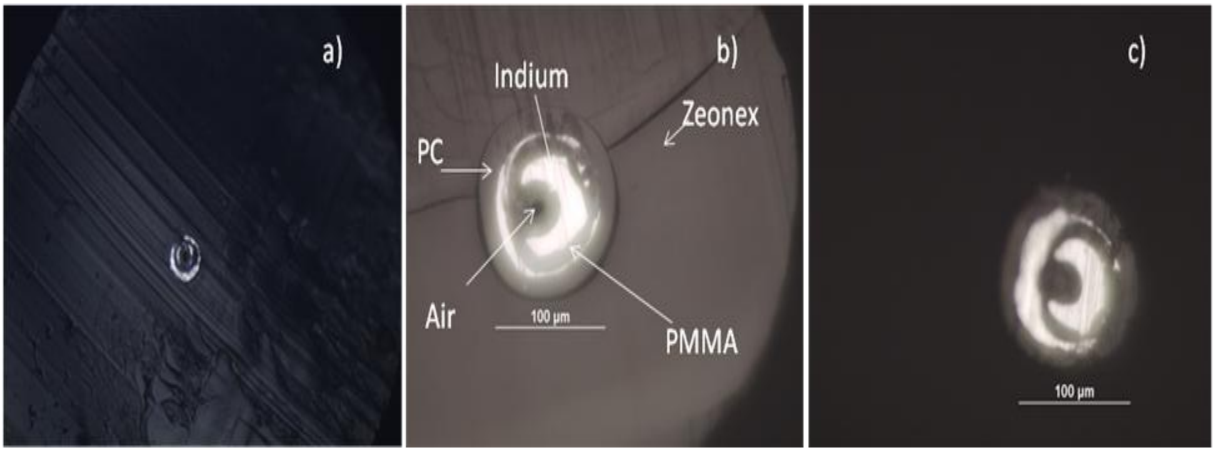

Figure 2: Double split ring resonator directly drawn in a fibre geometry. This resonator has a magnetic resonance at 0.24THz

Further, we made great progress in fabrication techniques, demonstrating the direct drawing of *double* split ring resonator fibres, which are smaller compared to the wavelength than single split ring resonator and are thus more promising for fabrication of waveguide structures we have derived in our numerical work. One article on this topic is in preparation [9]. Our work has received considerable attention in the optics community: we have been invited to present at one of the major metamaterial conferences (META 2011, Barcelona, October 2011)[4] and three major photonics conferences (CLEO/Conference on Lasers and Electro-Optics, San Jose May 2012 [6], ECOC/European Conference on Optical Communications, 2012 [7], OECC/OptoElectronics and Communications Conference 2012[8]).

Detailed results can be found in the attached publications.

Future Work: Future work will encompass both theory and experiment. We will need to extend our theoretical framework to incorporate losses and spatial dispersion, and run full three dimensional numerical simulations of actually drawn structures to match. Fabrication will concentrate on the integration of several double split ring resonator fibres into a single subwavelength waveguide.

Conclusion: The project has been extremely successful, demonstrating that deep subwavelength guidance in drawn-metamaterial is possible. Further work is required to extend these techniques from the terahertz spectrum to shorter wavelengths.

Publications:

Journal papers:
[1] Alessandro Tuniz, Richard Lwin, Alexander Argyros, Simon C. Fleming, Elise M. Pogson, Evan Constable, Roger A. Lewis, and Boris T. Kuhlmey, "Stacked-and-drawn metamaterials with magnetic resonances in the terahertz range," Opt. Express **19**, 16480-16490 (2011) http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-19-17-16480

Conference papers:
[2] A. Tuniz, R. Lwin, A. Argyros, S. C. Fleming, E. M. Pogson, E. Constable, R. A. Lewis, and B. T.

Kuhlmey, "Direct-Drawn Metamaterial Fibers with Magnetic Response in the 100GHz Range," in *Proceedings of the International Quantum Electronics Conference and Conference on Lasers and Electro-Optics Pacific Rim 2011*, (Optical Society of America, 2011), paper C676. http://www.opticsinfobase.org/abstract.cfm?URI=CLEOPR-2011-C676

[3] Shaghik Atakaramians, Alexander Argyros, Simon Fleming, Boris Kuhlmey, “Sub-wavelength modes in uniaxial metamaterial clad fibers,” Meta’12 — 3rd International Conference on Metamaterials, Photonic Crystals and Plasmonics, (Paris, April 2012).

Invited and keynote talks:

[4] B. T. Kuhlmey, A. Tuniz, Elise M. Pogson, R. A. Lewis, and S. C. Fleming “Drawn metamaterials,” Metamaterials '2011: The Fifth International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (Barcelona, October 2011)

[5] B. T. Kuhlmey, “Drawn metamaterials” Ringberg Workshop, Russell Group of the MPI for the Science of Light, 2011

Upcoming invited talks:

[6] Simon Fleming, Alessandro Tuniz, Alexander Argyros, Boris T. Kuhlmey, “Metamaterials Fabricated by Drawing” Conference on Lasers and Electro-Optics (CLEO), San Jose May 2012 (invited)

[7] Simon Fleming, Alessandro Tuniz, Alexander Argyros & Boris Kuhlmey, "Metamaterials Drawn in Fibers", Invited Paper at the 38th European Conference on Optical Communications (ECOC 2012), Amsterdam, (16-20 September, 2012)

[8] Simon Fleming, Alessandro Tuniz, Alexander Argyros & Boris Kuhlmey, "Metamaterials in Fibers", Invited Paper at the 17th OptoElectronics and Communications Conference (OECC 2012), Busan, Korea, (July 2-6, 2012)

In preparation:

[9] Neetesh Singh, Alessandro Tuniz, Richard Lwin, Alexander Argyros, Simon C. Fleming, Shaghik Atakaramians and Boris T. Kuhlmey, “Fiber Drawn Double Split Ring Resonators in the Terahertz Range,” in preparation.

[10] S. Atakaramians, A. Argyros, S. C. Fleming and B T. Kuhlmey “Hollow-core uniaxial metamaterial clad fibers: Part I – modal equations and guidance conditions”

[11] S. Atakaramians, A. Argyros, S. C. Fleming and B T. Kuhlmey “Hollow-core uniaxial metamaterial clad fibers: Part II – dispersive metamaterials”